2012-09

Study of Command and Control (C&C) Structures on Integrating Unmanned Autonomous Systems (UAS) into Manned Environments

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http://hdl.handle.net/10945/17468

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

STUDY OF COMMAND AND CONTROL (C&C) STRUCTURES ON INTEGRATING UNMANNED AUTONOMOUS SYSTEMS (UAS) INTO MANNED ENVIRONMENTS

by

Kine Yin Tham

September 2012

Thesis Advisor:	Gary Langford
Second Reader:	John Osmundson

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704–0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202–4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704–0188) Washington DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** September 2012	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE Study Of Command And Control (C&C) Structures on Integrating Unmanned Autonomous Systems (UAS) into Manned Environments			**5. FUNDING NUMBERS**
6. AUTHOR(S) Kine Yin Tham			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943–5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ______N/A______.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

The use of unmanned systems in the military has been growing. Although the technologies and associated capabilities of unmanned autonomous systems (UAS) continue to progress rapidly, comparatively little has been considered about how these systems will impact a future operating environment. This thesis used scenario planning, specifically a slice-of-time scenario planning, to explore the future operating environment and examined integrating UAS into the current manned environment. This thesis highlighted a few technologies which will shape the future of unmanned systems. The thesis also explored a case study based on STARFISH Project by the Acoustic Research Laboratory (ARL), a laboratory within the Tropical Marine Science Institute (TMSI) of the National University of Singapore (NUS), and derived a proposed roadmap for integrating unmanned systems into the manned environment.

14. SUBJECT TERMS Unmanned systems, Autonomy, Scenario Planning			**15. NUMBER OF PAGES** 83
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540–01–280–5500

Standard Form 298 (Rev. 2–89)
Prescribed by ANSI Std. 239–18

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STUDY OF COMMAND AND CONTROL (C&C) STRUCTURES ON INTEGRATING UNMANNED AUTONOMOUS SYSTEMS (UAS) INTO MANNED ENVIRONMENTS

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MASTER OF SCIENCE IN SYSTEMS ENGINEERING

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ABSTRACT

The use of unmanned systems in the military has been growing. Although the technologies and associated capabilities of unmanned autonomous systems (UAS) continue to progress rapidly, comparatively little has been considered about how these systems will impact a future operating environment. This thesis used scenario planning, specifically a slice-of-time scenario planning, to explore the future operating environment and examined integrating UAS into the current manned environment. This thesis highlighted a few technologies which will shape the future of unmanned systems. The thesis also explored a case study based on STARFISH Project by the Acoustic Research Laboratory (ARL), a laboratory within the Tropical Marine Science Institute (TMSI) of the National University of Singapore (NUS), and derived a proposed roadmap for integrating unmanned systems into the manned environment.

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LIST OF ACRONYMS AND ABBREVIATIONS

ALFUS WG	Autonomy Levels for Unmanned Systems Working Group
ARL	Acoustic Research Laboratory
AUV	Autonomous Underwater Vehicle
C&C	Command and Control
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DSAAV	Distributed Software Architecture Autonomous Vehicle
DVL	Doppler Velocity Log
GICHD	Geneva International Centre for Humanitarian Demining
GPS	Global Positioning System
GRASP	General Robotics, Automation, Sensing and Perception
HRI	Human-Robot Interaction
LRIP	Low Rate Initial Production
LS3	Legged Squad Support System (from DARPA)
MCV	Missile corvette
MDA	Milestone Decision Authority
MINDEF	Ministry of Defence
MUM	Manned-Unmanned
NASA	National Aeronautics and Space Administration
NUS	National University of Singapore
RAND	Research And Development
RPC	Remote Procedure Call

RSN	Republic of Singapore Navy
STM	Small Tactical Munitions
TMSI	Tropical Marine Science Institute
UAS	Unmanned Autonomous Systems
UAV	Unmanned Aerial Vehicle
UNet-PANDA	Underwater Networked Pop-Up Ambient Noise Data Acquisition
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle

EXECUTIVE SUMMARY

While the technologies and associated capabilities of unmanned autonomous systems (UAS) continue to progress rapidly, comparatively little is known about how these systems will impact a future operating environment. This is premised on the fact that the unmanned systems are new and for which there is little experience. It is also premised on the fact that the human controllers do not yet know the limitations and capabilities of the unmanned systems. This thesis aims to highlight the implications of integrating UAS into the manned environment and to gain insights into desired command and control (C&C) structures.

The research applied the approach of scenario building based on the "slice-of-time" method in order to answer the research questions with "slice-of-time" scenario building. This scenario building examined the UAS in a future slice-of-time and explored the desirable characteristic of the UAS in a fully autonomous environment. This thesis highlighted a few technologies that will shape the future of unmanned systems.

The author's work focused on the first two phases, (1) Concept and Technology Development, and (2) System Development and Demonstration of the United States Acquisition Process. The thesis also explored a case study based on the STARFISH Project by the Acoustic Research Laboratory (ARL), a laboratory within the Tropical Marine Science Institute (TMSI) of the National University of Singapore (NUS). It also examined a timeline in which a real-life unmanned system conducted the required Concept and Technology Development and System Development and Demonstration. Using the case study and understanding of the acquisition process resulted in a proposed roadmap for integrating unmanned systems into a manned environment.

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ACKNOWLEDGMENTS

This thesis would not have been possible without the steadfast guidance and patience of my thesis advisor, Professor Gary Langford. Thank you for getting my research process off the ground and seeing through all my difficulties.

I would also like to extend great thanks to my second reader, John Osmundson, for his insight and help, especially towards the end, in making this work come to fruition.

Finally, and most importantly, I want to thank the three ladies in my life, Jenny, Jolie and Jamie. Thank you for all your patience and support to see me through this important phase of my work. I can finally have some fun with you all now.

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I. INTRODUCTION

The Republic of Singapore Navy (RSN) completed a naval exercise on May 15, 2012, which involved integrated operations between the Formidable-class frigate and the frigate's organic naval helicopters, as well as a multi-dimensional exercise encompassing anti-air, anti-surface and anti-submarine warfare. More importantly, the recently upgraded Victory-class missile corvette (MCV) demonstrated the use of the MCV's organic Unmanned Aerial Vehicle (UAV), ScanEagle UAV (S. Tan 2012). However, this was not the first time that the RSN had operated with an unmanned system.

The RSN earlier operated with the Protector, an Unmanned Surface Vehicle (USV) during the RSN's RSS Resolution's (Endurance-class Landing Ship Tank) three-month deployment to the North Arabian Gulf in 2004 (Wan 2007). The Protector USV was used during that deployment to assist in the mission of protecting critical installations from terrorist attacks. This was achieved by the USV intercepting boats and instructing them away from the critical installations. The boats complied even when there was no man aboard the USV.

The naval exercise on May 15, 2012 underscored the exciting, changing time that has dawned upon the RSN by integrating unmanned systems. The Minister of Defence (Singapore) highlighted this integration into a single system in his interview with the press during the naval exercise quoted in the following:

> The general point about our (Singapore) Army, Navy and Air Force is that now we're fighting as a system, rather than as individual compartments, and that makes us very much more effective. (Dr. Ng [Minister of Defence, Singapore] 2012)

A. PROBLEM STATEMENT AND RESEARCH QUESTIONS

While the technologies and associated capabilities of unmanned autonomous systems (UAS) continue to progress rapidly, comparatively little is known about how these systems will impact a future operating environment. This is premised on the fact that the unmanned systems are new so there is little experience. It is also premised on the fact that human controllers do not yet know the limitations and capabilities of the

unmanned systems. Similarly, integrating autonomous systems into existing organizational structures and Command and Control (C&C) architectures has not been explored. This thesis aims to highlight the implications of integrating UAS into the manned environment and gain insights into desired C&C structures. Thus, this research will seek to answer the following questions:

- How to integrate unmanned systems onto existing platforms?
- How should unmanned autonomous systems (UAS) be integrated into a manned environment given the potential differences in the Command and Control (C&C) structures?

B. METHODOLOGY

The traditional way of planning for an improvement in capabilities is taking an existing platform with its old capability and integrating a new capability. An example of this is that which was introduced in the opening paragraph of RSN integrating the ScanEagle UAV capability onto the existing Victory-class MCV. This method of improving capability of an existing system is incremental in nature with a high level of confidence for success as there is little risk in taking small steps. This traditional way of planning, however, leads to the inevitable problem of having to make compromises. Compromises such as in the earlier example of RSN's integrating ScanEagle UAV, the Victory-class has lost its anti-submarine sonar capability. There have also been comprises on the radar signature of the ship as there are more structures on board the top deck (Ministry of Defence (MINDEF) Singapore 2012). The alternative to integrating a new element is to design a new system from an empty slate and not having to deal with compromise. Otherwise, in order to integrate, trade spaces are examined and explored to choose the most efficient solution in terms of operationalizing the new capability in the shortest time on an existing platform

This research applied the approach of scenario building based on the "slice-of-time" method and will seek to answer the research questions with "slice-of-time" scenario building. This scenario building will examine the UAS in a future slice-of-time and explore the desirable characteristic of the UAS in a fully autonomous environment. The C&C structure was explored in this future slice-of-time. This thesis focused on the

first two phases of Concept and Technology Development and System Development and Demonstration. Using a real life unmanned system as a case study, this thesis examined the timeline that a real-life unmanned system has taken to conduct the Concept and Technology Development and System Development and Demonstration. A comparison was made on the existing C&C structures of traditional incremental planning and implications highlighted to make recommendations for the continual effort of integrating UAS into the current manned environment.

C. ORGANIZATION OF THESIS

The thesis consists of five chapters. Chapter I provided background along with the scope and methodology used. Chapter II described the literature review into different scenario planning, technological improvement and Command and Control. Chapter III introduced a case study. Chapter IV described in detail the slice-of-time scenario that is used for analysis in this thesis and established the necessary environmental assumptions used as well as developed the slice-of-time scenario. Chapter V provided conclusion and recommendations for future research.

D. CHAPTER SUMMARY

This chapter provided the rationale and overview of the thesis as well as its scope, benefits, and research methodology.

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II. LITERATURE REVIEW

A. SLICE-OF-TIME SCENARIO

Chapter II describes in detail the slice-of-time scenario method that is used for analysis in this thesis.

B. SCENARIO PLANNING

Organizational change occurs all the time in different magnitudes. In Chapter I, this thesis introduced the naval exercise carried out by the Singapore Navy which is an example of an organizational change. A study into such organizational change is difficult as the environmental contexts in which the organizations exist are themselves also changing. The environmental context change often occurs at an increasing rate and is of increasing complexity. An example of this is the increased complexity in software needed to support hardware in the Typhoon Eurofighter aircraft (Eurofighter n.d.). The aircraft is aerodynamically unstable and is unable to be flown by humans without a computer controlling the aircraft's stability. This environment context changed from one that involved only hardware to an environment that will need software to drive hardware. Therefore, the uncertainty in a study into organizational change or for a decision-maker in strategic planning is compounded by an increasingly dynamic and uncertain environment (Emery and Trist 1965).

Scenario planning is a useful tool in strategic planning and is beneficial in simplifying the complexity in environmental context change. The complex environment context can be isolated in scenario planning with a simpler context and understanding of a simpler causal relationship. Scenario planning is not new and has been in use for several decades. Large complex organizations have used scenario planning as a disciplined method for imagining the possible futures events, such as Shell International Petroleum Company (Royal Dutch/Shell Group, in the Netherlands) since the early 1970s before the 1973 Oil Shock (Schoemaker and van der Heijden 1993). In the mid-1980s, Shell created scenarios that focused on the future of the Soviet Union because that

country was a major competitor in the European gas market. That planning was used as part of the process to generate and evaluate the Shell's strategic options (Schoemaker and van der Heijden 1993).

1. Scenario Planning Differs From Other Planning Methods

Scenario planning differs from other types of planning methods. Schoemaker has highlighted the differences in scenario planning when compared to three other types of planning methods: (1) contingency planning, (2) sensitivity analysis and (3) computer simulations (P. J. Schoemaker 1995).

First, contingency planning is more focused on one specific uncertainty, such as "What if the engine of the ScanEagle[1] stopped working, will the ScanEagle be able to safely glide on a landing path?" Contingency planning presents a base case and the exception or contingency. Scenario planning is more holistic in consideration. Scenario planning explores the joint impact of various uncertainties. It considers holistically the joint impact of various uncertainties giving them equal weightage in determining the follow up action plan for these uncertainties.

Second, sensitivity analysis examines the effect of a specific change of one variable while keeping all other variables constant. This is a very systematic and scientific method of observing the response of a system to a specific variable of interest (Blanchard and Fabrycky 2010). As the name suggests, sensitivity analysis makes is appropriate for small changes in one variation, while the remaining variations stay constant. Sensitivity analysis does not make sense when change is large (Daradkeh, Churcher and McKinnon 2008). Often a large change in one variation will affect other variations making them difficult to remain constant. An example is examining the flying characteristic of the ScanEagle in different atmospheric temperatures. If the variation in atmospheric temperature is small, sensitivity analysis of atmospheric temperature to the stalling angle of can be conducted. However, if the variation of atmospheric temperature is large, air pressure will be affected. This may also result in different wind speed if there

[1] ScanEagle (SE) is an Unmanned Aerial Vehicle (UAV) built by Insitu, a subsidiary of Boeing. http://www.mindef.gov.sg/imindef/news_and_events/nr/2012/may/15may12_nr/15may12_fs3.html

is a large change in atmospheric temperature (Eastern Illinois University n.d.). Sensitivity analysis is not of much value then. Scenarios instead “try to capture the new states that will develop after major shocks or deviations in key variables” (P. J. Schoemaker 1995).

Third, scenarios are more than just the output of a complex computer simulation model. Scenarios instead attempt to interpret output by identifying patterns and clusters the many computer simulations might generate. Scenario planning often includes elements that are subjective and which can be difficult to be objectively represented in computer simulations. “Scenario planning simplifies the avalanche of data into a limited number of possible states.” (P. J. Schoemaker 1995)

2. Purpose of Scenario Planning

The purpose of using scenarios is to give a credible context in which to explore options in a particular scenario’s context. When two or more scenarios are thought out, comparison and contrast can be done on the alternatives. The objective of the scenario is to project an analytical schema from which alternatives can be extrapolated, compared and contrasted. It is not employed for figuring out different plans that can be used when different scenarios unfold, but provides this analytical schema so that specific important causal factors and interactions can be investigated in greater detail. Scenario planning will be able to reveal potential consequences “that are often overlooked in general or abstract analyses and discussions” (Kahn and Wiener 1967). Simply put, scenarios are “tools for ordering one’s perceptions about alternative future environments, in which one’s decisions might be played out” (Schwartz 1991).

Peter Schwartz describes several steps in the scenario development process in his work, The Art of the Long View. These steps include: identify the focal issue or decision; identify the key forces and trends in the environment; rank the driving forces and trends by importance and uncertainty; select the scenario logics; fill out the scenarios; assess the implications; and select the leading indicators and signposts for monitoring purposes (Schwartz 1991, 226–234).

The similarities in the steps for developing scenarios, as described by Morrison and Mecca, are that they are narrative descriptions of possible futures. A single scenario

represents a history of the future. There may be many different paths that can lead to this future, and a single scenario is but one of the histories of this future (Morrison and Mecca 2003). Morrison and Mecca comprehensively described the various steps to be taken into consideration in developing scenarios. An example is the scenario of the “most likely” future. This scenario contains all of the forecasts (developed from an earlier forecasting activity) in a narrative, weaving them together from some point in the future, describing the history of how they unfolded. In this manner, the scenario will encompass the logic for setting the contexts of forecast future. Alternatives to this future are based upon the occurrence or nonoccurrence of particular events in the event set. The range of uncertainty inherent in the different scenarios (which are, themselves, forecasts) changes the assumption that the future will be an extrapolation from the past (Morrison and Mecca 2003). Within the context of an alternative future depicted by a scenario, the decision-maker can identify causal relationships between environmental forces, the probable impacts of these forces on the organization, the key decision points for possible intervention, and foundations of appropriate strategies (Kahn and Wiener 1967); (Martino 1993). By providing a realistic range of possibilities, the set of alternative scenarios facilitates the identification of common features likely to have an impact on the organization no matter which alternative occurs.

Therefore, the purpose of scenarios is not to produce an accurate picture of the intended operational environment. Of course, if one is able to do so, it will be an added benefit. Instead, scenarios help stakeholders make strategic decisions about the stakeholders’ future, collaborate together and orient the stakeholders’ action as necessary as they discover from the context created by the scenarios. The focus for the stakeholders is to understand the causal relationships between the environmental forces and identify the main driving forces and the areas of uncertainty. In summary, scenarios communicate ideas, clarify relationships, and describe the alternative outcomes of the dynamics of a system.

3. Types of Scenarios

There are many approaches that can be taken in writing scenarios. These range from as simple as a single person writing a description of a future situation to as complicated as using an interactive computer model to generate outlines of many alternatives. Morrison and Mecca described that there are four distinct types of scenarios:

- demonstration scenario
- driving-force scenario
- system-change scenario
- slice-of-time scenario

The first three types are characteristic of "path-through-time" narratives; the fourth is a "slice of time" narrative. This thesis will examine the four different types of scenario in detail in the following sections (Morrison and Mecca 2003).

a. Demonstration Scenario

Herman Kahn, Harvey DeVeerd, and a few others at RAND (Research And Development) Corporation were the first to pioneer the demonstration scenario. A non-profit global policy think tank, RAND was first formed to offer research and analysis to the United States armed forces by Douglas Aircraft Company in the early days of systems analysis (RAND Corporation 2011).

In a demonstration scenario, the writer first imagines a particular end-state, in the future, and then describes a distinct and plausible path of events that could lead to that end-state. There is another version of the demonstration scenario in which it considers branch-points. Branch-points are decisive events for which crucial choices are made along the plausible path of events that it represents. These branch-points are the focus of the policy attentions and not the final outcome (or the end-state that was first imagined starting out the demonstration scenario process). As Kahn and Wiener point out, demonstration scenarios answer two kinds of questions: (a) how might some hypothetical situation come about, step by step, and (b) what alternatives exist at each step for preventing, diverting, or facilitating the process? (Kahn and Wiener 1967)

A demonstration scenario is useful in both stimulating and disciplining the imagination. It is much like the usefulness of the other three scenario types as described in the following sections. The major weakness of the demonstration scenario, as Morrison and Mecca highlight, is that it is based upon “genius’’ forecasting or experts’ opinions, and is, therefore, dependent upon the idiosyncrasies and experiences of individuals (Morrison and Mecca 2003).

b. Driving-Force Scenario

The driving-force scenario is a popular type of scenario in governmental and business planning as exemplified by Schwartz (Schwartz 1991). The writer first devises a “scenario space” by identifying a set of key trends, specifying at least two distinctly different levels of each trend, and developing a matrix that inter-relates each trend at each level with the others. For example, two driving forces are GNP growth and population growth. If each driving force is set to “high,” “medium,” and ‘‘low,’’ there are nine possible combinations which define the scenario space and the context of a possible future. The writer’s task is to describe each of these futures, while assuming the driving-force trends remain constant.

The purpose of the driving-force scenario is to clarify the nature of the future by contrasting alternative futures with others in the same scenario space. It may well be that certain policies would fare equally well in most of the futures, or that certain futures may pose problems for the institution. In the latter case, decision-makers will know where to direct their monitoring efforts.

The key usefulness of driving-force scenario is that the analysis of strategic choice is simplified to a function of considerable value (e.g., “high,” “medium,” and ‘‘low”). This takes place at the beginning of conducting the analysis when the search for key variables is most perplexing among the vast possibilities of variables. Simplification is at the key of this driving-force scenario. The major weakness of the driving-force scenario is the assumption that the trend levels are fixed. This assumption ignores all the potential events that might affect the trend. It is akin to turning a deaf ear

to a traffic warning of congestion when choosing a driving route home. The experience one gets from the selected route may not be reflective of the route's normal condition.

c. System-Change Scenario

The system-change scenario is designed to explore systematically, comprehensively, and consistently the interrelationships and implications of a set of trend and event forecasts. This set, may be developed through scanning. Scanning is the systematic collection of external environmental information in order to lessen the randomness of information received by an organization. It is providing context or trend evaluation to information. This set of trend and event forecasts embraces the full range of concerns in the social, technological, economic and political environments. Thus, system-change scenario type varies both from the demonstration scenario (which leads to a single outcome and ignores most or all of the other developments contemporaneous with it) and from the driving-force scenario (which accounts for a full range of future developments but assumes that the driving trends are unchanging), in that there is no single event that caps the scenario, and there are no a priori driving forces.

The system-change scenario depends upon cross-impact analysis to develop the outline of alternative futures. The writer must still use a good deal of creativity to make each alternative intriguing by highlighting key branch points and elaborating on critical causal relationships. Cross-impact analysis of events from the various scenarios also defines the upper and lower envelopes of each trend projection.

The system-change scenario's major weakness is the same criticism that can be applied to driving-force and demonstration scenarios: all of the input data and relationships are judgmental. There is a great deal of subjectivity and experts' opinion to these scenarios. Another weakness is that the envelopes that bound the trend projection by itself provide no guidance in deciding which of the many alternative futures that can be generated should serve as the basis for writing scenarios. This choice must be made using such criteria as "interest," "plausibility," or "relevance" (Morrison and Mecca 2003).

d. Slice-of-Time Scenario

A slice-of-time scenario jumps to a future period in which a set of conditions comes to fruition, and then describes how stakeholders think, feel, and behave in that environment. The objective of slice-of-time scenario is to summarize a perception about the future or to show that the future may be more (or less) desirable, fearful, or attainable than is currently generally thought (Morrison and Mecca 2003). If period within "slice-of-time" is wide, say from 1990 to the year 2000, it is possible to identify the macro-trends over this period (Naisbitt 1990). The strength of this approach is the narrow temporal focus with the pretense of an attached reference to time. This is a typical dimension in which people often think. The weakness of this approach is there is no explanation as to the influences on the direction of these trends, no plausible description of how (and why) the influences change over time.

C. TECHNOLOGY THAT SHAPED THE FUTURE UNMANNED SYSTEMS

1. DARPA Competition

The ongoing efforts to allow UAVs to exist in a manned environment will be shown. A relatively complex urban environment is similar in many ways to the maritime environment of congested straits. The Defense Advanced Research Projects Agency (DARPA) Grand Challenges is a prize competition for driverless vehicles, funded by the DARPA. These Grand Challenges started in 2005 with unmanned cars driving through deserts and then in 2007 the Urban Challenge competition attempted navigation through a mock urban environment (Defense Advanced Research Projects Agency (DARPA) 2007). The DARPA Grand Challenge evolved to unmanned cars interacting in a mock urban environment as shown in Figure 1. This series of competitions has shown it is possible to allow for autonomous vehicles to co-exist in a manned environment. It is very plausible that in the near future some autonomous vehicles will exist in a maritime environment, too.

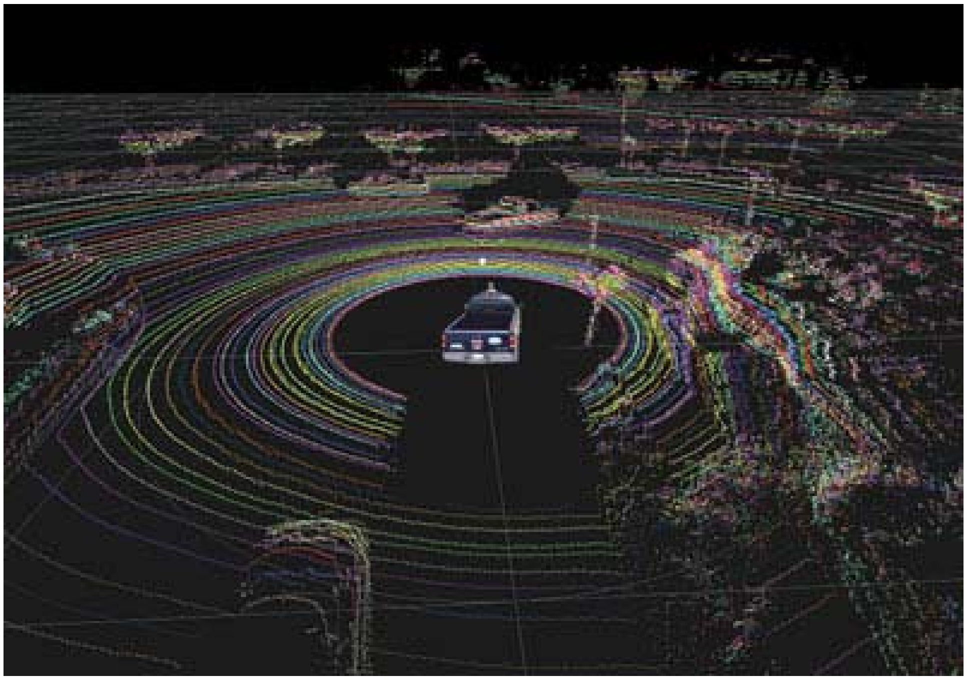

Figure 1. DARPA Urban Challenge Viewed Synthesized from the Car’s Laser Scanner (From Greenberg 2007)

Google Company had embarked on the Google Car Project since the DARPA Grand Challenge and has reported that its automated cars, manned by trained operators (mainly for safety reason as the car are more than capable of driving through the manned environment without any operator intervention), have driven from the Google company’s Mountain View campus to its Santa Monica office. The automated car has gone on to Hollywood Boulevard, down Lombard Street, crossed the Golden Gate Bridge, navigated the Pacific Coast Highway, and traveled all the way around Lake Tahoe. The self-driving cars have logged over 140,000 miles since October 9, 2010 (Google 2010) pictured here in Figure 2.

Figure 2. Google Car (From Google 2010)

2. True Force Multiplier

Unmanned Autonomous Systems (UAS) are a true force multiplier. The resources and efforts that are poured into enabling a single unmanned autonomous vehicle to perform a particular task need only be invested once. The single vehicle that has learnt to carry out its task can be easily scaled up and replicated in an entire swarm of UAS. This scaling up can enable an entire swarm of UAS to carry out incredible missions which can also be seen as an emergent property of a swarm of UAS. Seeing what the researchers at The General Robotics, Automation, Sensing and Perception (GRASP) Laboratory, University of Pennsylvania (Engineering) have achieved with a swarm of flying mini flying quadrotors, the future of swarm UAS is inspired (GRASP Laboratory 2012). A still photo of a flying demonstration from KMel Robotics, (maker of the quadrotors) during The Saatchi & Saatchi New Directors' Showcase 2012 at Cannes Lions International Festival of Creativity on 17–23 June 2012, is shown in Figure 3. This illustrates some of the many different emergent properties from a swarm of flying mini flying quadrotors and efforts put in put the many different producers and designers.

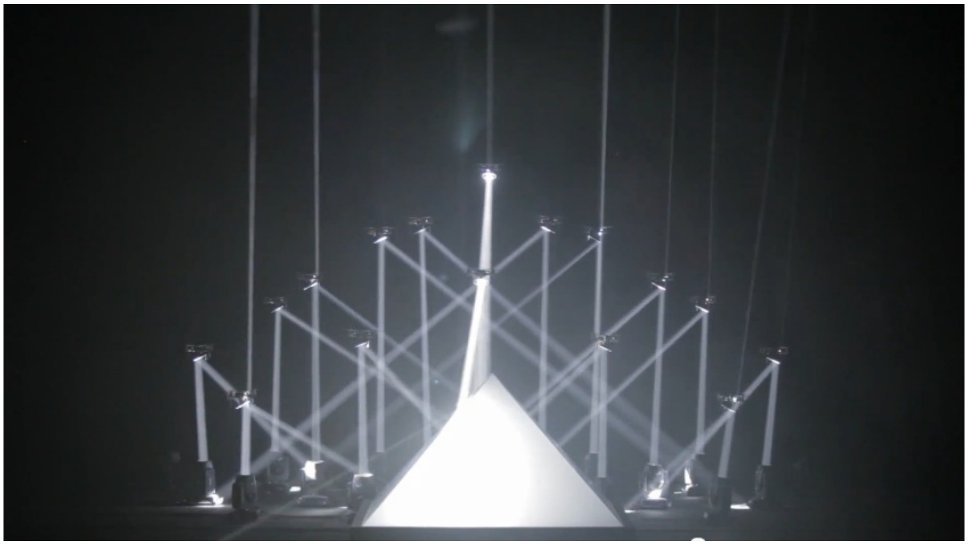

Figure 3. Swarm of quadrotors showcasing their emergent properties (From KMel Robotics 2012)

3. Nanotube-Reinforced Carbon Fiber Piranha USV

A ZPM's nanotube-reinforced carbon fiber prepreg (already impregnated with a synthetic resin) is normally associated with high-performance composite powerboats. The use of such ultra-lightweight materials in an unmanned surface vessel (USV) makes sense as this will increase USV endurance allowing it to remain in the operation area for a longer period therefore making them deployable in more situations. Built entirely of Arovex™, the newly announced 54-foot Piranha USV weighs only 8,000 pounds, yet can carry a 15,000 pound payload 2,500 miles. The high weight to carrying capacity makes the platform suitable for missions as diverse as anti-piracy, search and rescue, submarine hunting, and harbor patrol with a range of armament options that includes stabilized machine guns, Mark 54 torpedoes, and over-the-horizon missiles.

Future versions will leverage the Piranha USV's reconfigurable payload capacity for a wide range of missions, including anti-piracy, surface surveillance, surface action, mine countermeasures, electronic warfare, and antisubmarine warfare.

> The Piranha USV provides real opportunity to use unmanned vessels as a true force multiplier," said Russell Belden, VP Advanced Composite Solutions and Director of the Piranha USV Program at ZPM (Zyvex Marine 2011). It is designed to perform a wide variety of missions like

> anti-piracy, search and rescue, submarine hunting, and harbor patrol. Since the Piranha is an unmanned surface vessel, it will reduce the risk to the warfighter and provide greater capability for those missions at a dramatically lower cost. This craft provides real opportunity to use unmanned vessels as a true force multiplier.
>
> The U.S. Navy and Coast Guard are facing a looming budgetary crisis with little relief in sight," said James Hasik, principal at Hasik Analytic, a defense industry consulting firm that has been working with ZPM to refine the USV's operational concept and marketability to military customers (Zyvex Marine 2011). "A cost-effective unmanned vessel like the Piranha, with its range and payload, could provide the numbers and capabilities to significantly augment the current fleets, and help to control the seas from the Caribbean to the Mediterranean, the Persian Gulf, and the Horn of Africa.

In particular, the Piranha USV could be a very useful tool for combating modern piracy. Capable of cruising long distances to escort single ships or convoys, it can use advanced sensors and networked satellite or terrestrial communications to be able to provide continuous persistent presence to detect pirates or other hostiles before they can threaten shipping.

> Surface navies have been clamoring for unmanned systems that can truly deliver useful capabilities," said Lance Criscuolo, president of ZPM (Zyvex Marine 2011). "The Piranha USV offers the U.S. and its allies the platform they need to bring the advances in unmanned aerial systems from the sky to the water. ZPM has a history of developing materials for lighter, more efficient products. We're very proud to apply this knowledge and offer a USV to keep the waters safe and our sailors out of harm's way.

Construction of a Piranha USV prototype is underway, and was to begin sea trials in the second quarter of 2010. In 2011, Zyvex Marine shipped the first production nano-composite vessel (Zyvex Marine 2011).

Figure 4. Zyvex Marine's Piranha USV (Zyvex Marine 2011)

4. Pyros Small Tactical Munitions

Raytheon's new Pyros small tactical munitions went to an end-to-end live firing test on July 18, 2012 (Raytheon Company 2012). A single Pyros was dropped from a Cobra unmanned air vehicle (UAV) to demonstrate the glide bomb's semi-active laser and Global Positioning System (GPS) guidance modes, its height-of-burst sensor for standoff detonation above a target and the multi-effects warhead. These can be seen from the company's live firing video shown on their website (Raytheon Company 2012).

The live firing simulated targeting simulated insurgents planting an improvised explosive device. While directly over the target, the warhead detonated at a predetermined height following inputs from the weapon's height-of-burst sensor. The Pyros is a gravity-dropped bomb that is guided to dead center of the target. It is then detonated at a preset height over the target to permanently terminate the threat.

At 13.5 pounds (6.1 kg) in weight, 22 inches (56 cm) in length, and 3.6 inches (9 cm) in diameter, Pyros is the smallest air-launched weapon in the Raytheon portfolio – small enough to be dropped from the U.S. military's common launch tube.

Originally sporting a seven-pound (3.2 kg) warhead, Raytheon says the new warhead removed two pounds (0.9 kg) of weight while providing improved blast-fragment characteristics (Raytheon Company 2012). Costing in the neighborhood of U.S.$35K per unit, Pyros is built for delivery via UAV, but is also well suited for light

attack aircraft such as the Hawker Beechcraft AT-6B, which could carry dozens of Pyros small tactical munitions (STMs) on missions.

Having a wingspan of 10.2 feet (3.1 m), a length of 9.3 feet (2.8 m), and a takeoff weight over 100 pounds (45 kg), the Raytheon Cobra is about one-third the size of the better known General Atomics MQ-1 Predator and could easily be mistaken for a "giant-scale" radio controlled model airplane, some of which have wingspreads greater than 20 feet (6.1 m) and weigh well over two hundred pounds (91 kg) (Raytheon Company 2012).

In fact, the Cobra's single engine is a Desert Aircraft DA-150 air-cooled, two-cycle, two-cylinder power plant, designed for giant-scale model planes, which produces 16.5 horsepower from just over nine cubic inches (150 cc) displacement, and weighs eight pounds (3.6 kg).

Figure 5. Pyros being fitted onto a Cobra unmanned air vehicle (Raytheon Company 2012)

D. COMMAND AND CONTROL (C&C)

1. Differences in Command and Control

In order to better understand Command and Control, consider the functions "to command" and "to control," and conduct a functional decomposition of them. The

decomposed process of "to command" (or "to direct") is shown in Figure 6. In the case of the other decomposed processes "to control" is shown in Figure 7. From the figures, the differences between command and control can be seen from the decomposed subprocesses. Therefore, when considering a C&C architecture for unmanned systems, it is similar to integrating a system. If the integrating of the system is predicated on commanding and directing (or controlling), it is essential to separate the functions so that the proper allocation can be made to physical entities and so the users of the system can be exposed to the most effective functions to carry out their work (Langford, *Engineering Systems Integration*, 2012).

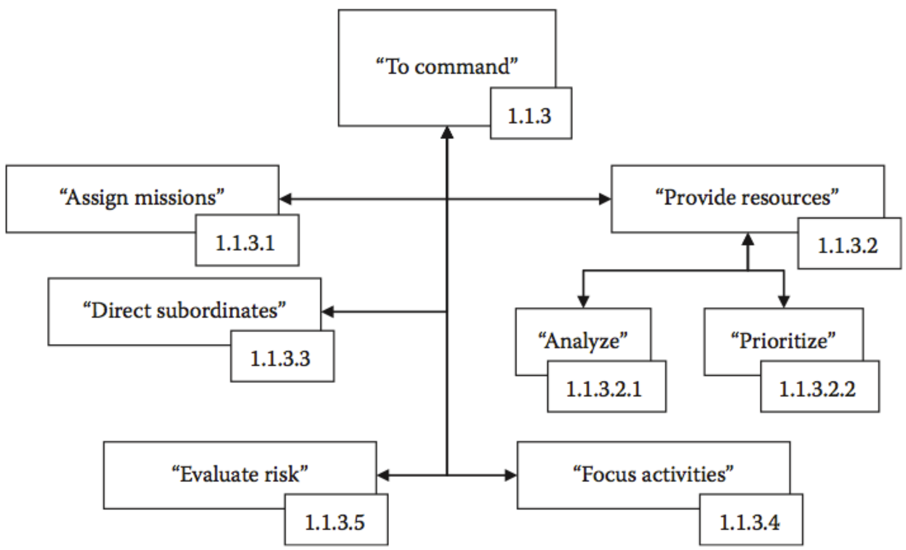

Figure 6. Decomposition of "To Command" Process (From Langford, *Engineering Systems Integration*, 2012)

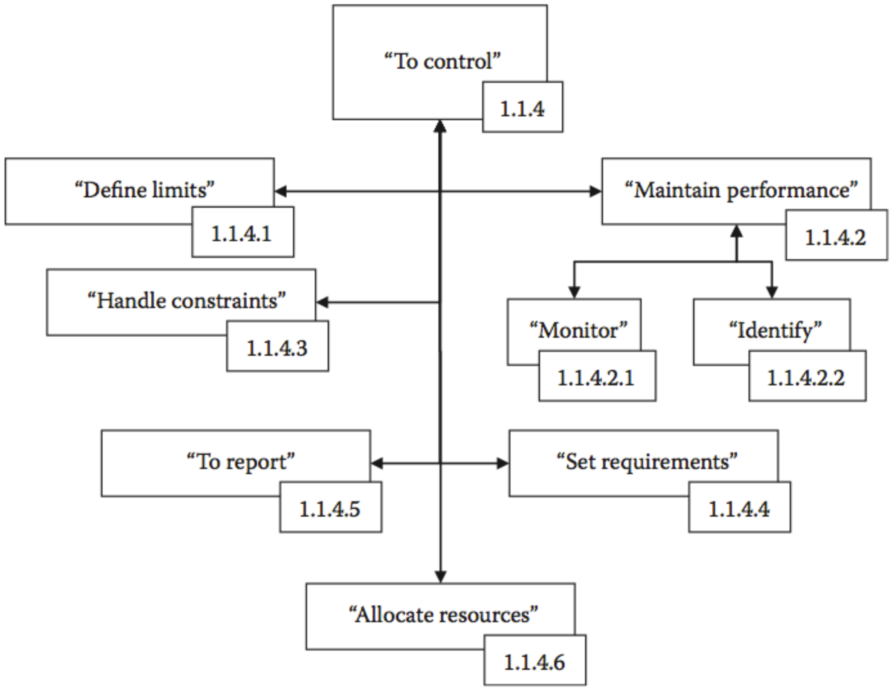

Figure 7. Decomposition of "To Control" Process (From Langford, *Engineering Systems Integration*, 2012)

E. CHAPTER SUMMARY

In order to have a different analysis of how unmanned autonomous systems (UAS) can be integrated into manned environments, this chapter suggests using a slice-of-time scenario to project a future period where the environment will be that systems are unmanned and autonomous. In this scenario space, the question of integrating man into such an environment can be examined, and determination made if such future integration is attainable. This chapter also introduced some of the technologies that affect unmanned systems and their integration space into the manned environment. This chapter also looked into the difference in command and control. The following chapters will examine this possibility in details.

III. CASE STUDY

A. INTRODUCTION

> Oftentimes, lessons from previous projects (referred to as cases) can be assembled and reviewed to glean lessons. In developing an appreciation for how certain aspects of these projects seemed to affect or be affected, the power of hindsight is often too critical of the progress from one stage to the next. By the knowledge of the results of the project work or by ignorance of what actually transpired, lessons taken from these cases can be extracted and applied to similar, representative examples of current work studied. After a bit of review and introspection, patterns of behavior or events may develop that suggest a commonly occurring set of variables and outcomes. At some point, a behavioral model might be constructed that represents a more detailed examination of a portion of the lessons, grounded in a set of perspectives, measurement theory, and the objective actions. We refer to such a set as a case study. (Langford, *Engineering Systems Integration*, 2012)

Given the understanding of extracting lessons from case studies, this thesis will look at an unmanned system in development. With review, and observation for patterns of events, the objective is to piece together the probable timeline involved in the development of a real life unmanned system to aid in the projection of a roadmap for development of a fully autonomous unmanned system that will be integrated into a manned environment.

B. STARFISH: AN OPEN-ARCHITECTURE AUTONOMOUS UNDERWATER VEHICLES (AUV)

STARFISH is the name given to a small team of autonomous robotic fish - a project carried out by the Acoustic Research Laboratory (ARL), a laboratory within the Tropical Marine Science Institute (TMSI) of the National University of Singapore (NUS). The aim of the STARFISH project is to develop a team of modular, low-cost Autonomous Underwater Vehicles (AUVs) with a design that supports extensions to allow adding heterogeneous capabilities. The STARFISH project was started in 2006 as shown in Figure 8. The STARFISH AUVs have been designed with an open-architecture framework of mechanical, electrical and software interfaces. This modularity allows the users to easily reconfigure a team of AUVs according to field requirements. STARFISH

is not a single AUV, but a team of modular and cost efficient open-architecture AUVs. With these multiple base AUVs, users may easily configure heterogeneous teams of AUVs for collaborative missions. Users can also easily integrate their proprietary modules with other AUVs. Integration is not bound by hardware modules, but is extended to software subsystems that can be inserted and swapped within the vehicles. This grants the users flexibility to control and reconfigure a heterogeneous team of specialist AUVs (Y. T. Tan, M. A. Chitre, et al. 2011).

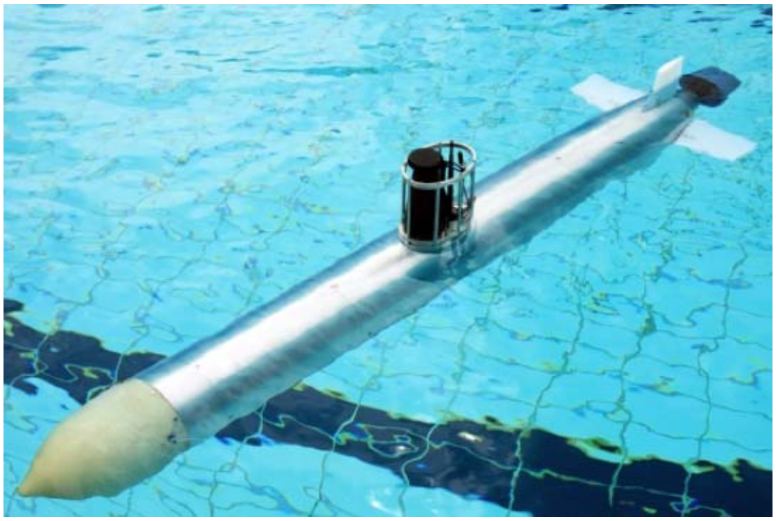

Figure 8. STARFISH AUV (From Tan 2008, 80)

1. Hardware Modularity

The STARFISH AUV has a modular hardware design that allows for adding special modular features to the payload to make the specific AUV perform a certain task as shown in Figure 9. This modular reconfiguration and integration are primarily achieved through a mechanical and electrical interface. The mechanical coupling interface uses a male-female interlocking mechanism with locking teeth, as shown in Figure 10. As the STARFISH AUV performs based on the concept of a team of AUVs, an individual AUV need not have all the sensors required for the mission. This is based on the force multiplier effect (as mentioned in Section II.C.2) of having a swarm of AUVs that will be able to complete any assigned mission.

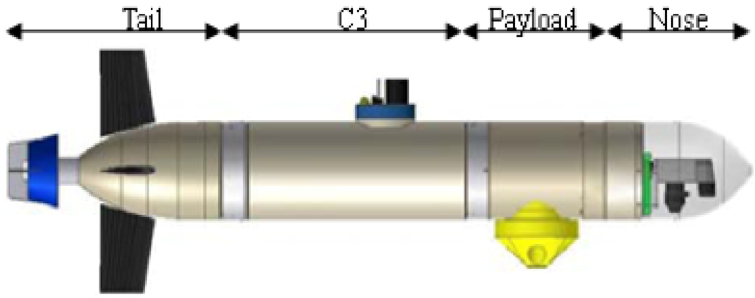

Figure 9. STARFISH AUV System Configuration (From Tan 2008, 80)

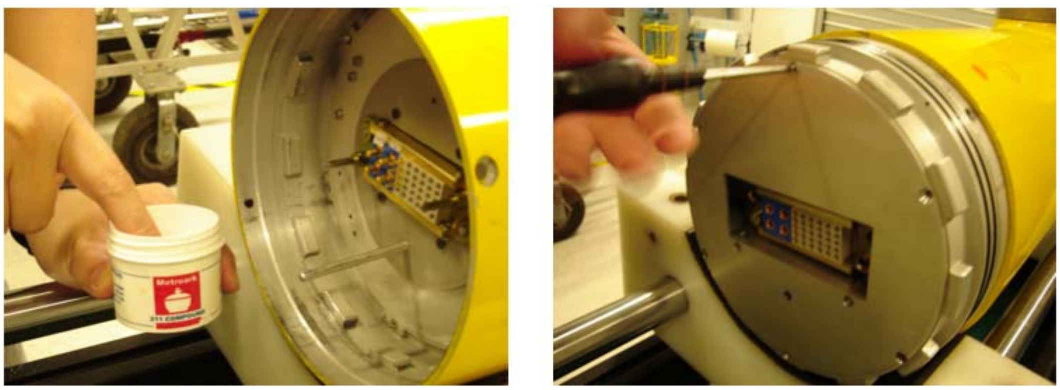

Figure 10. Male-female (Left-Right) Interlocking Mechanism (From Y. T. Tan, M. A. Chitre, et al. 2011)

2. Software Modularity

Operation of the STARFISH AUV components is based on Distributed Software Architecture Autonomous Vehicles (DSAAV) architecture. The DSAAV has been designed from the ground up with modular AUVs in mind, as shown in Figure 11. In a DSAAV compliant AUV, each module provides a uniform software interface that other AUV modules can access. This interface allows configuration of the module, logging of critical information, discovery of services, access to sensor and actuator services, health monitoring, and automated software update functionality. The interface is rich in functionality, yet lightweight and portable to ensure that even low power micro-controllers can easily implement it. The DSAAV can be implemented on any underlying communication backbone such as Ethernet. The software components running under

DSAAV are independent of the underlying communication backbone and function without change of various AUVs in different operating environments (Chitre 2008).

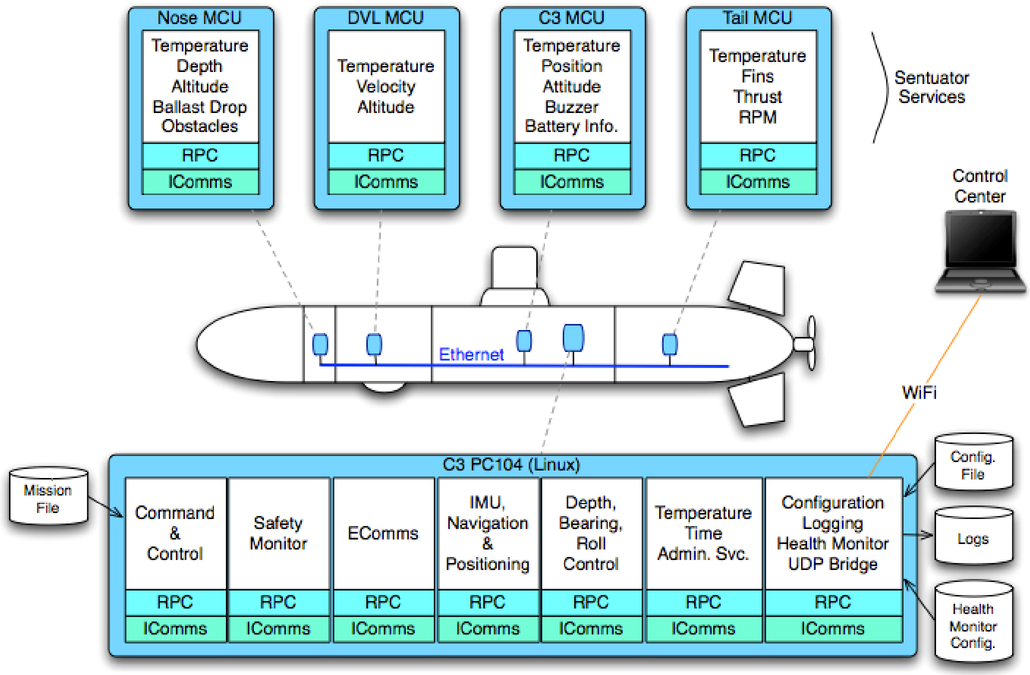

Figure 11. STARFISH AUV Software Modularity Configuration (From Chitre 2008)

The DSAAV has a four-layer architecture (1) IComms, (2) remote procedure call (RPC), (3) framework and sensor/actuator service, (4) command and control components as shown Figure 12. The bottom layer IComms provides an implementation of a reliable messaging service over whatever communications backbone available or chosen for the STARFISH AUVs that are teamed up for the particular assigned mission. The next higher RPC layer implements a remote procedure call semantic using the IComms messaging service. The third layer consists of framework and sensor/actuator services implemented using the RPC framework. These include core services for vehicle configuration, logging and health monitoring. The layer also includes hardware drivers for all the sensors and actuators as well as an external communications interface for communication to other vehicles and/or the control center. The top layer houses the command and control components which utilize the services provided by lower layers to achieve the mission of the vehicle (Chitre 2008).

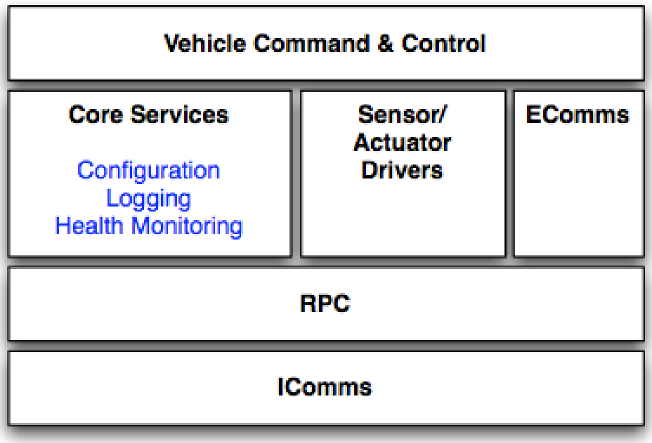

Figure 12. DSAAV's 4-layer Architecture (From Y. T. Tan, M. A. Chitre, et al. 2011)

3. Heterogeneous Multi-assets Deployment

STARFISH AUVs are designed with the vision of operating within the setup of heterogeneous autonomous assets. With modularity and flexibility of reconfiguration supported by the open architecture, the STARFISH allows easy adaptations of the vehicle to interoperate with other assets. Other assets can also take advantage of its flexible architecture. STARFISH AUV can be seamlessly deployed alongside other systems to form a set of collaborative assets; a possible configuration is depicted in Figure 13. In this configuration, assets with heterogeneous capabilities provide different functionalities to the team. For example, surface vessel USV and positioning AUV have provided good position fixes. Bottom mounted systems, such as Underwater Networked Pop-Up Ambient Noise Data Acquisition (UNet-PANDA), have been shown effective for ranging and data relaying, along with survey AUVs for data collection (Y. T. Tan, M. A. Chitre, et al. 2011). Many of these assets such as STARFISH AUVs, USV and surface vessel have employed variations of hardware and software configurations from the DSAAV architecture. This heterogeneous multi-assets deployment is a simple example of the possible setup in the perceived slice-of-time scenario. The scenario as suggested by Tan, Chitre, et al., is in line with the slice-of-time scenario of integrating many unmanned systems in a manned environment.

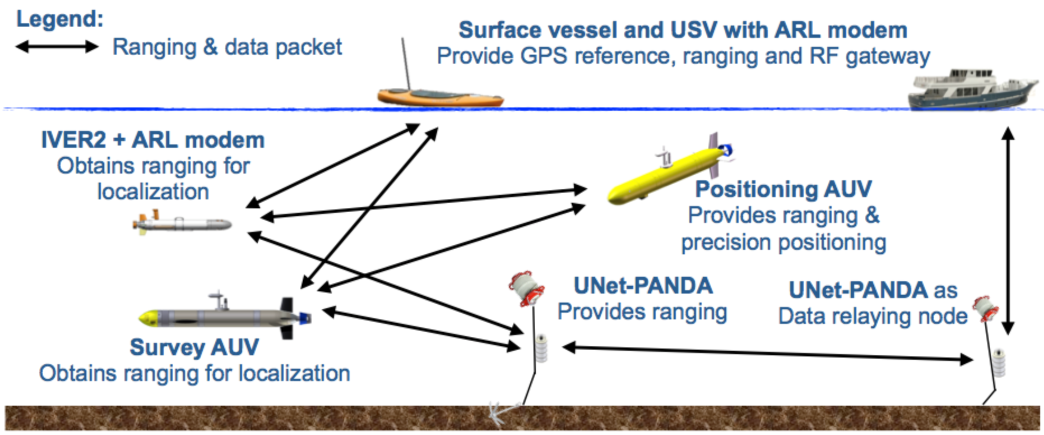

Figure 13. Homogeneous Multi-assets Deployment (From Y. T. Tan, M. A. Chitre, et al. 2011)

4. Cooperative Positioning between Two STARFISH AUVs

In a scenario where there are limited payloads for field deployment, a heterogeneous team of assets that can cooperate with one another would be advantageous. The ARL had worked on a team of STARFISH AUVs equipped with complementary payloads to accomplish a desired mission objective cooperatively. Two STARFISH AUVs, *Bluestar* and *Redstar* were configured as beacon (positioning AUV) and survey AUV, respectively. *Bluestar* was equipped with a Doppler Velocity Log (DVL) payload to execute its role as a positioning beacon. On the other hand, *Redstar* was equipped with a sidescan payload for the purpose of bottom imaging (Koay, et al. 2011).

Figure 14. Cooperative Positioning with *Bluestar* and *Redstar* (From Koay, et al. 2011)

The AUV architecture has allowed easy adaptation of STARFISH AUVs into these complimentary configurations. Specific payloads with appropriate software services have been introduced and only adaptation in the position estimate software modules have been needed while the rest of the of the software modules were unchanged (Koay, et al. 2011).

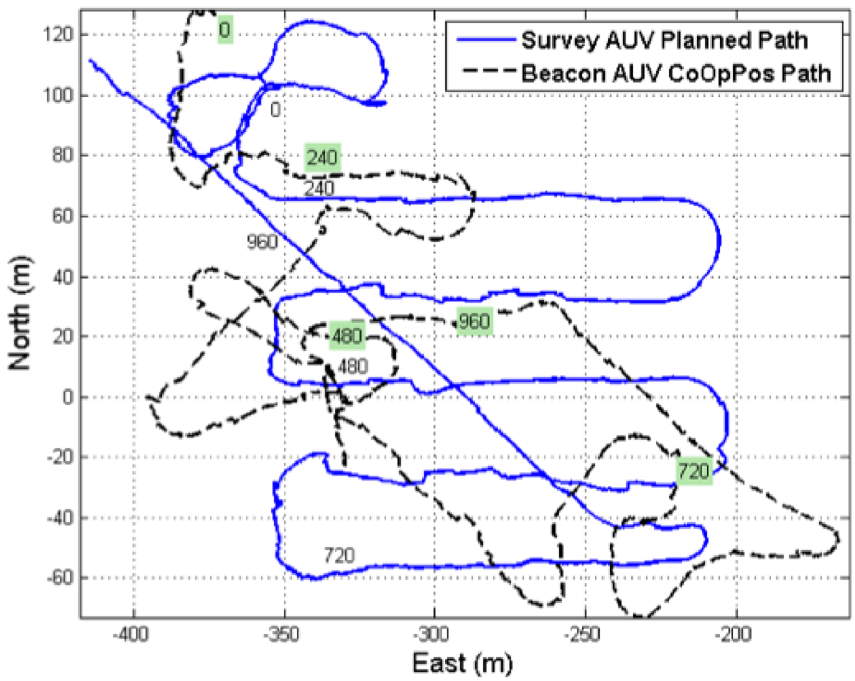

Figure 15. Cooperative Positioning Results: Mission Path (From Koay, et al. 2011)

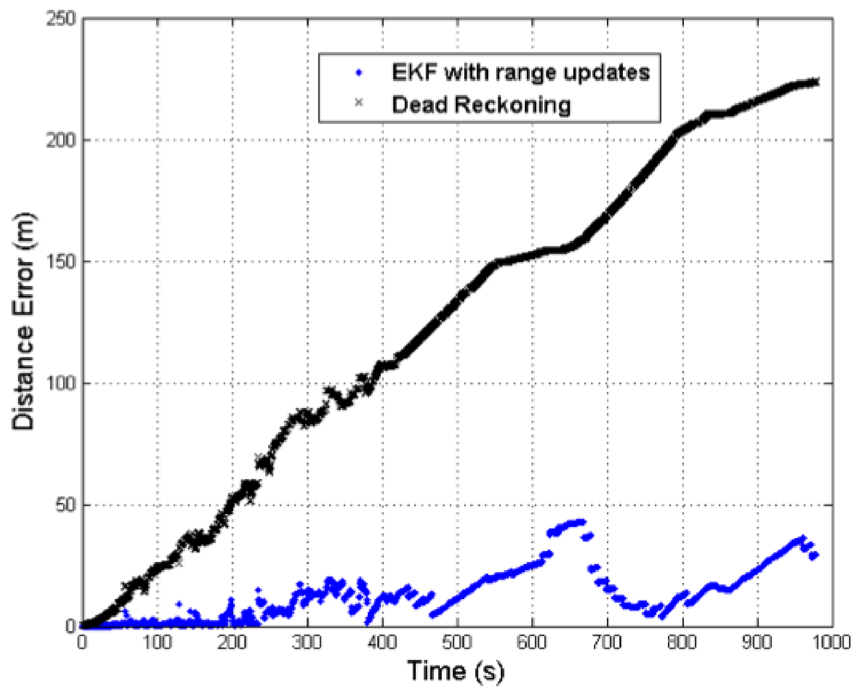

Figure 16. Cooperative Positioning Results: Error of *Redstar* (From Koay, et al. 2011)

Several open-water trials were carried out in coastal waters in Selat Pauh, Singapore where *Redstar* performed surveys in lawn-mover missions using only dead-reckoning for position estimates and ranging information from *BlueStar* to improve positioning accuracy. The mission path executed by *Bluestar* and *Redstar* can be observed in Figure 15. The bounded positioning error of *Redstar* is shown in Figure 16. The results clearly exhibited the efficiency of cooperative positioning, where positioning errors of a simply equipped AUV without high accuracy positioning capabilities could still yield good bounded estimates.

Cost savings in terms of payload deployment was also achieved. Effectively, the required quantity of the DVL and sidescan payloads was reduced by one each as compared to equipping every AUV with both DVL and sidescan. The reduced in number of sensors needed also increased the operational and logistics efficiencies since there are less parts to operate or maintain (Y. T. Tan, M. A. Chitre, et al. 2011).

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IV. SLICE-OF-TIME SCENARIO

Chapter II establishes the necessary environmental assumptions used as well as develops the slice-of-time scenario. From this baseline scenario, an integrated system of manned and unmanned autonomous systems is described in Chapter IV.

A. DESCRIPTION OF THE SLICE-OF-TIME SCENARIO

1. Material Technology Improvement

The unmanned systems will benefit from the material technology improvement that is occurring in manufacturing industries. The nanotube-reinforced carbon fiber Piranha USV highlighted in Section II.C.3, gave an example of how the currently development of unmanned systems is at the fringe of material technological improvement that will provide unmanned systems with sufficient endurance to be properly deployed to conduct operations. The greatly increased endurance will drive the possibility of unmanned systems being tasked into more operations in the slice-of-time scenario. This is similar in idea to the electric vehicle which previously suffered from low endurance making it unsuitable to replace a combustion engine vehicle (Roos n.d.), but is seeing a gradual replacement with longer endurance models coming into the market such as the Nissan Leaf introduced to the United States in 2010 (Nissan 2010).

2. Prevalent Unmanned Systems

Examples of the development of unmanned vehicles, starting from the DARPA Grand Challenges (described in Section II.C.1), they showed that unmanned systems will be operating in manned environments sooner than might have been expected. There will be a need for robust C&C architecture to govern the entire integration space. The perceived slice-of-time scenario provide an environment in which unmanned systems can be prevalent and while working amidst a manned assets.

3. Swarm of Unmanned Systems

Unmanned systems will likely be operating in swarms, since the true force multiplier effect (described in Section II.C.2) of any unmanned systems is when the

unmanned systems can reach a critical mass number that is beyond the capability that can be obtained from manned systems. The emergent behaviors of a swarm of unmanned systems need to be well identified in this slice-of-time scenario. Similarly, there needs to be a for robust C&C architecture that can able to handle not just unmanned systems but swarms of unmanned systems in the perceived slice-of-time scenario environment.

4. Suitable Arsenal for Unmanned Systems

Unmanned systems operating in swarm will likely be small in size. The development of more small size tactical weapons (described in Section II.C.4) will enable more unmanned systems to be able to carry out a wider spectrum of operations in the perceived slice-of-time scenario. These suitable arsenals will enable more unmanned systems to operate in the future.

B. AUTONOMY

The understanding of autonomy is important in the slice-of-time scenario and this following section will provide further details.

1. Unmanned and Autonomy

The difference between the two terms (unmanned and autonomy) makes clear that not all unmanned vehicles are autonomous. Autonomy requires a higher level of sophistication. This section seeks to clarify the difference of autonomy from unmanned. The term “manned” is defined as “Having a crew” and “unmanned” is defined as “Lacking a crew” (Lewis 2006–2012). Both terms, manned and unmanned, have been quite widely used and have been clear since the National Aeronautics and Space Administration (NASA), the United States’ civilian space agency, successfully embarked on the Apollo Program and completed the manned mission to moon on July 20, 1969 (National Aeronautics and Space Administration (NASA) 2009) and when the Curtiss-Sperry Aerial Torpedo became the first “unmanned” flying bomb (also known as “Curtis-Sperry Flying Bomb” on March 6, 1918 as shown in Figure 17. This was the dawn of the unmanned aerial vehicle flying (Newcome 2003).

Figure 17. Curtiss/Sperry “Flying Bomb” (From Parsch 2005)

In general terms, autonomy is defined as “The capacity of a system to make its own decisions about its actions” (Lewis 2006–2012). With the development of unmanned systems into the realm of autonomy, there was a need for a specific definition. In 2003, the Federal Agencies Ad Hoc Autonomy Levels for Unmanned Systems (ALFUS) Working Group (WG) defined and collected terminology to support the Group’s main objective, the definitions of the unmanned system autonomy levels and the metrics for measuring autonomy levels. The ALFUS WG had been able to give a specific definition and metrics to define autonomy (Federal Agencies Ad Hoc Autonomy Levels for Unmanned Systems (ALFUS) Working Group (WG) 2004). The ALFUS WG definitions of autonomy are in two parts “(A) The condition or quality of being self-governing; and (B) An unmanned system’s A UMS’s own ability of sensing, perceiving, analyzing, communicating, planning, decision- making, and acting, to achieve its goals as assigned by its human operator(s) through designed human-robot interaction (HRI). Autonomy is characterized into levels by factors including mission complexity, environmental difficulty, and level of HRI to accomplish the mission” (Huang et al. 2004).

2. ALFUS Autonomy Framework

The ALFUS comprehensive framework which provides levels of autonomy that can be described. The framework includes the following:

- Terms and Definitions: A set of standard terms and definitions that support the autonomy level metrics.
- Detailed Model for Autonomy Levels: A comprehensive and detailed specification for determining autonomy. The audience consists of technical users of unmanned systems.
- Summary Model for Autonomy Levels: A concise, scalar presentation of autonomy levels. The audience is executives and end users (in the DoD domain, these would include combat leadership, program managers, unit leaders, and soldiers).
- Guidelines, Processes, and Use Cases: A process to translate the detailed, technical ALFUS model into the summary model as well as guidelines to apply the generic framework to specific ALFUS models. A number of use cases may be generated to demonstrate the application processes.

Of these, the most interesting to note for this thesis is the detailed model for autonomy levels. The detailed model is a comprehensive set of metrics that represent multiple aspects of concerns, including (a) mission complexity, (b) environmental difficulty, and (c) level of HRI that, in combination, indicate a unmanned system's level of autonomy. This detailed model is illustrated in Figure 18.

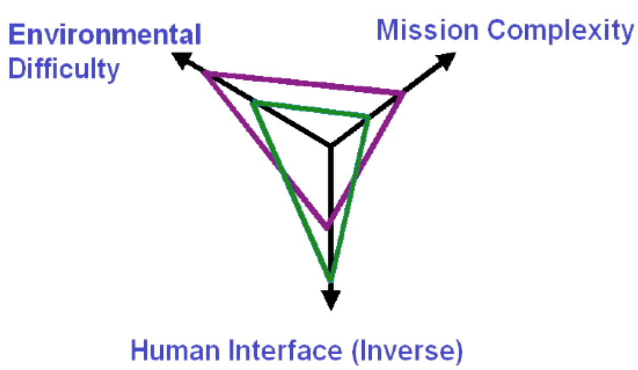

Figure 18. Three dimensions determining the autonomy level for unmanned systems, detailed model (From Huang et al. 2004)

a. Environmental Difficulty

The level and measurement for Environmental Difficulty is complex and closely intertwined with the other two measures. However, Environmental Difficulty should stand out as a separate aspect due mainly to the large variety of Environmental Difficulty. This measure is decomposed into categories including, but not limited to:

Static Environment, Dynamic Environment, Electronic/Electromagnetic Environment, Mobility, Mapping and Navigation, Urban Environment, Rural Environment, and Operational Environment. This aspect has not been fully explored by ALFUS and will need further explorations (Huang et al. 2004). However, a clear takeaway is that the level of autonomy will need to be higher for a higher level of Environmental Difficulty.

b. Mission Complexity

The detailed model specified and evaluated the autonomy level according to the missions and tasks that the unmanned systems are capable of performing. The more complex the missions are, the higher the level of autonomy required is. An example is that an unmanned system capable of performing a security surveillance task is regarded as having a higher level of autonomy than a system that is only able to perform a point-to-point driving task.

There are four major categories of metrics for measuring the complexity of missions (Huang et al. 2004). They are:

- Tactical Behavior: The composition and structure of the involved tasks provide an essential measure for the complexity of a mission.
- Coordination and Collaboration: A mission with a higher level of complexity typically requires a higher level of coordination and collaboration among the components or subsystems. From a system perspective, a UMS that is able to perform a high level of coordination and collaboration should be regarded as having a high level of autonomy.
- Performance: A UMS's ability to achieve mission goals with high efficiency and accuracy through its planning and execution components indicates the UMS's autonomous capability.
- Sensory Processing/World Modeling: The perception requirements for particular missions and the dependency on external information indicate levels of complexity of the missions.

Additionally, to those that are proposed by Huang, et al., the use of a loss function can be a metric that compares performance with normalized loss. Loss can be measured as energy, matter, material wealth, and information (Langford, *Engineering Systems Integration,* 2012).

c. Human Robot Interaction (HRI)

The detailed model also stated that the level of Human Robot Interaction (HRI) and the autonomy level for an unmanned system have a fairly linear relationship for simple systems. The HRI takes into account operator workload, required skill level and the ratio of operator to number of unmanned systems the operator controls. These are all relevant factors that have an inverse relationship with the autonomy of the unmanned systems (Huang et al. 2004).

3. Situational Awareness

When considering unmanned systems in a manned environment, it is important to take the human factor into account. An important concept within the field of human factors, which extends across issues of memory and comprehension, is that of situation awareness (Proctor and Zandt 2008). Situational awareness is the knowledge of objects and processes with respect to their spatial or temporal relations, as interpreted by a particular person, with a defined perspective, within an acknowledged paradigm, through the framework of a particular theory, as predicated by a set of principles. Being "aware" of a situation is the first step in being able to assess and evaluate the data gathered through situational awareness. Becoming situationally aware means knowing what data is, how it relates to form various bits of information, and how that information can be used in forming cognitive patterns (Langford, *Toward a General Theory of Systems Integration,* 2012). Situational awareness is arguably one of the most critical factors in any scenario. Situational awareness is defined as having three levels: (a) perception, (b) comprehension, and (c) projection (Bolstad, Costello and Endsley 2006).

a. Perception

Level 1 situation awareness, perception, involves the sensory detection of significant environmental cues. Perception is an active process whereby individuals extract salient cues from their environment.

b. Comprehension

Level 2 situation awareness, comprehension, involves integrating information into working memory to understand how that information will impact the individual's goals and objectives. This includes developing a comprehensive picture of the world, or of that portion of the world of concern to the individual.

c. Projection

Level 3 situation awareness, projection, consists of extrapolating information and projecting it forward in time to determine how it will affect future states of the operating environment. Level 3 situation awareness combines what the individual knows about the current situation with existing mental models or schemata of similar events to predict what might happen next.

As the complexity of environment, mission or Human Robot Interaction (described in the Section IV.B.2) increases, so does the cognitive workload required to achieve and maintain situation awareness in order to make accurate informed decisions (Bolstad, Costello and Endsley 2006). A visual representation of the three levels of situation awareness is shown in Figure 19. This figure illustrates the levels of cognitive processes that need to take place. The three levels of situation awareness show the heavy cognitive workload that an unmanned system will need to accomplish in order for the unmanned system to be able to function in a complex manned environment.

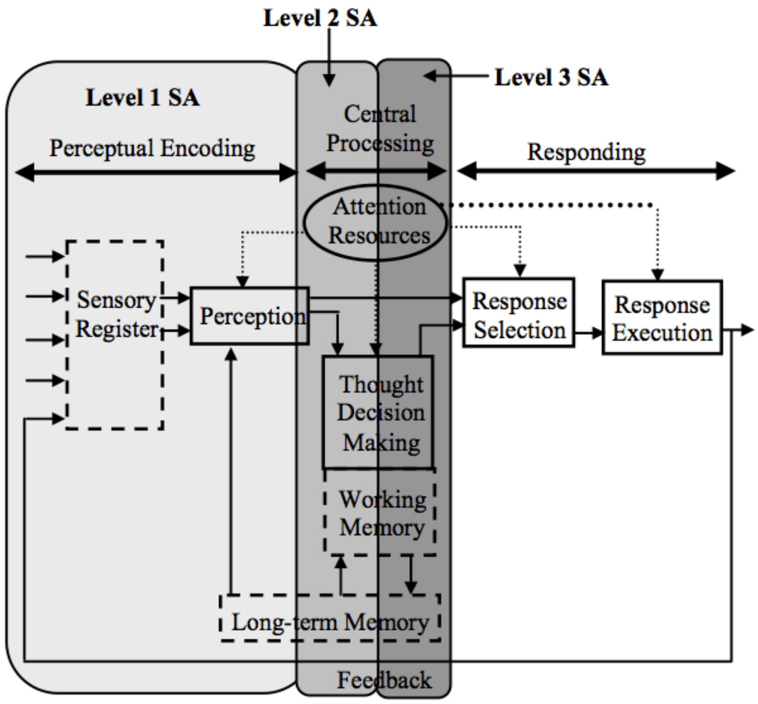

Figure 19. Information Processing for Situation Awareness (From Adams, 2007)

Having good situational awareness allows a human to carry out and complete missions. How would situation awareness be replicated in order for unmanned systems to perform autonomously? Shared situational awareness is more likely to be the characterization. Sharing suggests there is a common basis for communication and understanding, but perhaps with some unique identifiers that may be specific to a particular platform. These particulars may or may not be shared, but presumably could be requested or sent to a central body or distributed throughout a swarm of unmanned vehicles. The particulars could become part of the situational awareness if that information were found meaningful as part of the requisite knowledge. Current unmanned systems have demonstrated basic levels of environmental perception capability with the unmanned systems onboard sensors and (the ever increasing amount of) computing power. The (Defense Advanced Research Projects Agency (DARPA) Legged Squad Support System (LS3) demonstrated two robotic “pack mule” prototypes that can sense the rugged environment in which they are located and automate their movements to trot over rough, rocky terrain, easily transition to a 5-mph jog shown in Figure 20. The increased onboard sensors and computing power also enable the mules to

follow a squad leader. This ability of autonomy in terrain crossing while following the leader provides a demonstration of autonomy in the making (Defense Advanced Research Projects Agency (DARPA) 2012). This is still basic autonomy (as described in Section IV.B.1) and, in order to achieve situational awareness in unmanned machines, the challenges to be met are in the areas of comprehension and prediction. The logic algorithms in most unmanned systems (e.g., LS3) are highly reactive to their environment, without real comprehension of the overall mission goals of the squad. In order for the unmanned systems to reach a higher level of automation, (for example the next LS3 that will be able to carry out autonomous resupply missions to troops on the frontline,) there must be an advance in areas such as artificial intelligence, machine learning, and even advance modeling of artificial intelligence operating in a complex environment associated with human cognition.

Figure 20. Legged Squad Support System (LS3) (From Defense Advanced Research Projects Agency (DARPA), 2012)

This discussion of situation awareness leads to a discussion of how situation awareness is related in both human (operator or supervisors for the unmanned systems) and the unmanned systems. This relationship can be seen across the spectrum of

autonomy as introduced by Adam. The common factor is the degree of human interaction with the system in the course of the mission. Adams correlated levels of autonomy to levels of both system and human SA. Direct human control of the system, i.e., most current UVS, would equate to little, if any, machine situation awareness, while fully autonomous systems would reduce considerably the level of the need for human situation awareness (Adams 2007). The inverse relationship of human situation awareness (from the left) and unmanned system situation awareness (from the right) across the spectrum of increasing autonomy is shown in Figure 21.

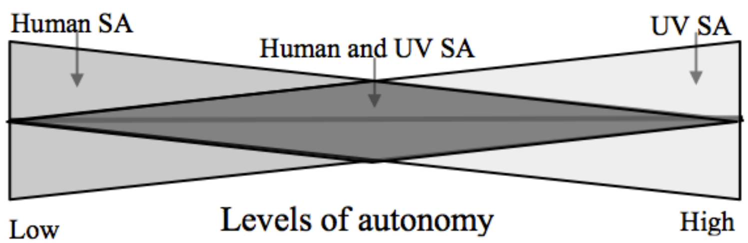

Figure 21. Allocation of Human and Unmanned System Situation Awareness across the Different Levels of Autonomy" (From Adam 2007)

Therefore, for the slice-of-time scenario planning of high level autonomy, the unmanned systems need to have a high level of situation awareness in order to effectively act as reliable collaborators to their human counterparts (in a man-unmanned teaming).

4. Manned-Unmanned (MUM Teaming)

In slice-of-time scenario planning, it is perceived that there will be a need for the unmanned systems to be continually operating in manned environments. Therefore, there is a need to discuss the notion of Manned-Unmanned (MUM Teaming). MUM teaming refers to the relationships established between manned and unmanned systems (Winnefield and Kendall 2010). The relationship is to form an integrated team of personnel engaged in a common mission incorporating both manned and unmanned systems. Thus, MUM teaming is the overarching term used to describe platform interoperability and shared asset control to achieve a common operational mission objective. Interoperability is the action of two or more systems or components as they interact and use the information that has been exchanged (Langford, *Engineering Systems*

Integration, 2012). This capability is vital for missions such as target cueing and handoff between manned and unmanned systems, where the operators require a high degree of geospatial fidelity to accurately depict each team member's location with regard to the object being monitored. It is perceived in the slice-of-time scenario planning that this fidelity will be achieved digitally through accurate data transfer, and there will be no need for any voice hand-over (Rider 2004).

In the United State Army, MUM teaming was also demonstrated by the follow-on Hunter Standoff Killer Team in 2006. During that demonstration, an AH-64D Apache helicopter executed a high level of interoperability control of a RQ-5B Hunter unmanned aerial vehicle (UAV) during a live fire exercise where the Apaches launched their own Hellfire missiles with the Hunter's sensor payload (IHS 2005). At these demonstrations, the Army Aviation Applied Technology Directorate successfully integrated a Mobile Commander's Associate (Defense Update 2005), including Link 16, and other data links, into an Army airborne C2 system. This integration enabled an airborne C2 system operator, located in a UH-60 Black Hawk helicopter, to control a Hunter UAV and its sensor, for the first time. The operator was also able to send and receive tactical information in flight between strike aircraft such as the FA-18, and reconnaissance aircraft such as JSTARS (Colucci 2004). These demonstrations have continued to support that slice-of-time scenario planning will have high level of MUM teaming (Winnefield and Kendall 2010).

5. Command and Control (C&C) of Multiple Unmanned System (One-to-Many)

In slice-of-time scenario planning, it is thought there will be a need for the unmanned systems to be controlled or supervised by the one user (one-to-many) C&C concept. It is expected that the user will be required to remotely communicate and control multiple unmanned systems since the unmanned systems alert and report situations will be beyond unmanned system autonomy and therefore require human interaction. It is further perceived there will be two forms of control in this slice-of-time scenario planning. As earlier discussed (Section IV.B.2.c) there will be limited human situation awareness in the high autonomy environment as illustrated in Figure 21. (Adams 2007) In

the slice-of-time-scenario, the forms of control need to be simple so that the human can conduct a one-to-many control. This thesis suggests that the C&C will take in the following two forms: (a) consent or (b) exception.

a. Consent C&C

In Consent C&C, the unmanned systems ask for user permission before starting an action. There is the worry about latency in this mode of C&C, but it will be used when the actions have high consequences and will require a human in the loop to make the executive decision. With unmanned systems operating with high autonomy, the unmanned systems will free up the user from having to control and execute all the action. With these high autonomy unmanned systems, the user will have more cognitive capacity to think critically and make necessary decisions. An example of these executive decisions is a "permission to destroy the target" request. This will occur while the unmanned systems are operated together in the same operating environment, and communicating and controlling their own actions in relation to other unmanned as well as manned systems. In slice-of-time scenario planning, it is likely there will be a high density of unmanned systems operating together and there is a need to plan for this happening. This is in line with the perceived idea of unmanned systems in the slice-of-time scenario operating in swarms to take advantage of the true force multiplier effect (in Section II.C.2)

b. Exception C&C

In Exception C&C, the unmanned systems will continue to carry out all their actions unless the user removes permission. An example of employing this capability in the future would be the ability to conduct mine clearance operations within a hostile environment. Mine clearance can be a monotonous (Geneva International Centre for Humanitarian Demining (GICHD) n.d.) and dangerous task well suited for unmanned systems that are not affected by monotony. An example in the slice-of-time scenario planning is a group of unmanned systems and unmanned underwater vessels (UUVs) carrying out tasks for a mission managed by a single mission human controller. The mission controller will establish the required mine clearance area for the group of UUVs.

The expectation of the controller is the UUVs will carry out their actions to accomplish the mission without the need to request permission to dispose of any mines found, as long as the situation is within the pre-cleared boundaries. These boundaries include physical boundaries that delimit the geographic area in which the mine-clearing operations are to be carried out, the functional boundaries by which interactions between the UUVs or the mines are contained, and the behavioral boundaries that determine how stakeholders will act according to the mine clearing operations and the consequences therefrom. If a UUV discovered a mine outside the approved boundary, (an example is the detection of the mine near an uncharted wreck,) the UUV is expected to report and wait for further instructions from the controller. Such high levels of autonomy and robust one-to-many C&C operations are deemed to be highly effective in the perceived slice-of-time scenario planning.

C. UNITED STATES DEPARTMENT OF DEFENSE (DOD) ACQUISITION PROCESS

The acquisition process for major defense systems is shown in Figure 22. The process is defined by a series of phases during which technology is characterized and matured into viable concepts, which are subsequently developed and readied for production, after which the systems produced are supported in the field (Department of Defense (DoD) 2012). The process allows for a given system to enter the set of activities at any of the developmental phases. For example, a system using unproven technology might enter at the beginning stages of the process and then proceed through a period of technology maturation; while a system based on mature and proven technologies might enter directly into engineering development, or conceivably, even production. There are four phases of development: (1) Concept and Technology Development, (2) System Development and Demonstration, (3) Production and Deployment and (4) Sustainment and Disposal (Department of Defense (DoD) 2012).

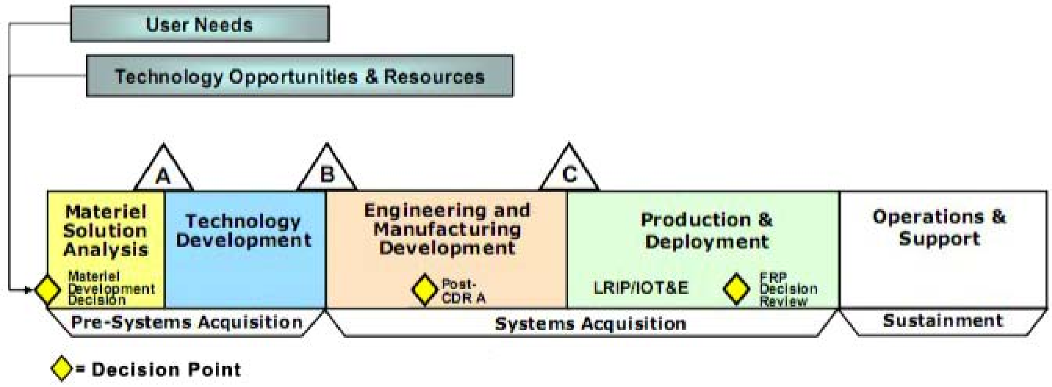

Figure 22. United States DoD Acquisition Process (From Department of Defense (DoD) 2012)

1. Concept and Technology Development

The first stage in the DoD acquisition process, Concept and Technology Development, is intended to explore alternative concepts based on assessments of operational needs, technology readiness, risk, and affordability. Entry into this phase does not imply that the DoD has committed to a new acquisition program; rather, it is the initiation of a process to determine whether or not a need can be met at reasonable levels of technical risk and at affordable costs.

2. System Development and Demonstration

The System Development and Demonstration phase could be entered directly as a result of a technological opportunity and urgent user need, as well as progressing through concept and technology development. The System Development and Demonstration phase consists of two stages of development, system integration and system demonstration. Depending upon the maturity level of a system, it could enter at either stage, or the stages could be combined. This is the phase during which the technologies, components and subsystems defined earlier are first integrated at the system level, and then demonstrated and tested. If the system has never been integrated into a complete system, it will enter this phase at the system integration stage. When subsystems have been integrated, prototypes demonstrated, and risks considered acceptable, the program will normally enter the system demonstration stage following an interim review by a Milestone Decision Authority (MDA) to ensure readiness. The system demonstration

stage is intended to show that the system has operational utility consistent with the operational requirements. Engineering demonstration models are developed and system level development testing and operational assessments are performed to ensure that the system performs as required. These demonstrations are to be conducted in environments that represent the eventual operational environments intended. Once a system has been demonstrated in an operationally relevant environment, it may enter the Production and Deployment phase.

3. Production and Deployment

The Production and Deployment phase consists of two stages: production readiness and low rate initial production (LRIP), and rate production and deployment. There exists a possibility that a system could enter directly into this phase if it were sufficiently mature, for example, a commercial product to be produced for defense applications. However, the entry is made directly or through the maturation process described, the production readiness and LRIP stage is where initial operational tests, live fire tests, and low rate initial production are conducted. Upon completion of the LRIP stage and following a favorable Beyond LRIP test report, the system enters the rate production and deployment stage during which the item is produced and deployed to the user. As the system is produced and deployed, the final phase, Sustainment and Disposal, begins.

4. Sustainment and Disposal

The last, and longest phase is Sustainment and Disposal. During this phase all necessary activities are accomplished to maintain and sustain the system in the field in the most cost-effective manner possible. The scope of activities is broad and includes everything from maintenance and supply to safety, health, and environmental management. This period may also include transition from contractor to organic support, if appropriate. During this phase, modifications and product improvements are usually implemented to update and maintain the required levels of operational capability as technologies and threat systems evolve. At the end of the system's service life, the system is disposed of in accordance with applicable classified and environmental laws,

regulations, and directives. Disposal activities also include recycling, material recovery, salvage or reutilization, and disposal of by-products from development and production.

This thesis focused on the first two phases of Concept and Technology Development, and System Development and Demonstration. Using a real life unmanned system as a case study, this thesis examined the timeline that the real life unmanned system has taken to conduct the Concept and Technology Development, and System Development and Demonstration.

D. ROADMAP FOR INCREASING CAPABILITY

1. Integrating Capabilities the Traditional Way

The traditional way of planning for an improvement in capabilities is by taking an existing platform with its old capability and integrating a new capability. An example is the Lockheed U-2, nicknamed "Dragon Lady," the single-engine, very high-altitude reconnaissance aircraft that has been in service since the 1950s.

> Even in an age of advanced spy satellites, U-2 still fills a crucial niche. Satellites and high-fliers like the U-2 or Global Hawk are completely complementary systems. Satellites do a fantastic job of quickly monitoring the entire globe but can't always focus on a particular area for a long time. High fliers do a great job of monitoring smaller areas for a long time," said Maj. Gen. James Poss, Air Force assistant deputy chief of staff for intelligence, surveillance and reconnaissance. (Brook 2011).

New capabilities have been constantly integrated into the old platform. The newest U-2 was built in 1989, and all U-2s have been updated with $1.7 billion spent since 1994 to retrofit them (Brook 2011). This method of improving capability of an existing system is incremental in nature. It has a high level of confidence for success, as there is little risk in taking small steps. This is illustrated in Figure 23. There is a gradual increase in capability with each new step of capability being integrated or introduced to the platform. This is a good systematic method but it can be time consuming. If there is a need for additional high capability (illustrated as the shaded ellipse in Figure 23.), the traditional way of planning will still have to take the path illustrated by the dotted line to reach the desired state.

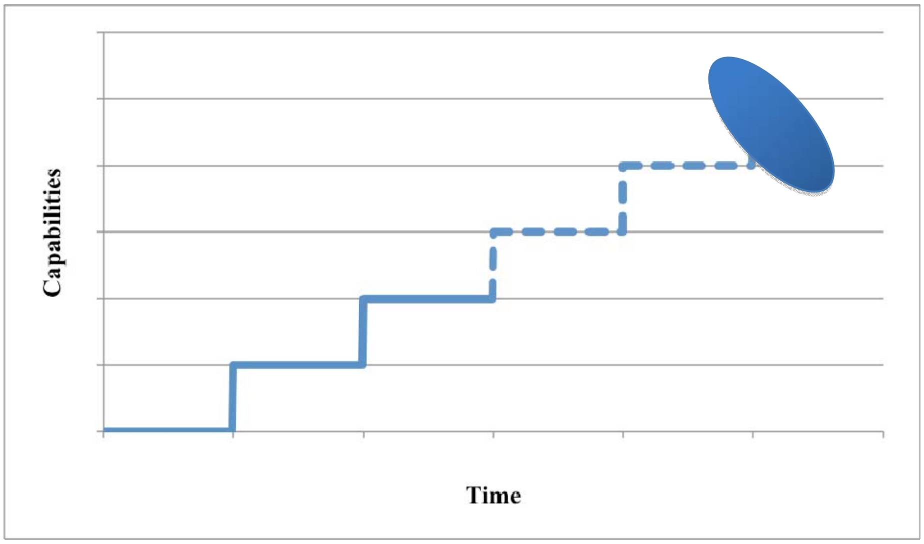

Figure 23. A Way of Incremental Increasing of Capability

The path that is moving up is the direction of “Want.” This is the path that is traditionally taken by operators since they are in “the thick of the action” where the immediate concern is about today’s war, about getting through the immediate problem. It is often this traditional method of responding to an immediate concern, “Want,” that creates the incremental path illustrated in Figure 24.

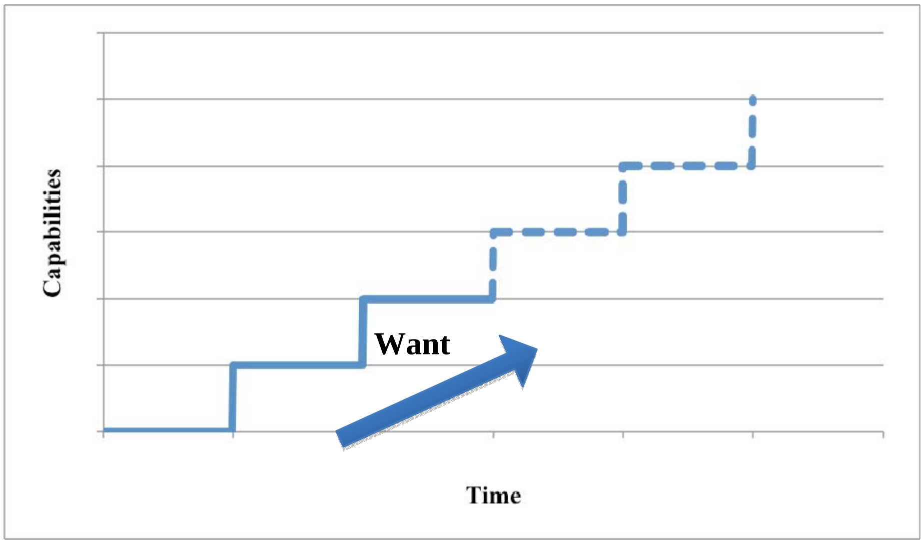

Figure 24. Direction of “Want”

However, if there is an envisioned ideal capability state as shown as the shaded ellipse in Figure 25. Then, it is possible to plan out a path of “Need.” This path is downward while trying to meet current capability. The benefit of this planning is that gaps and shortfalls can be identified and remedial actions can be planned in order for capability to be improved to reach the desired ideal capability.

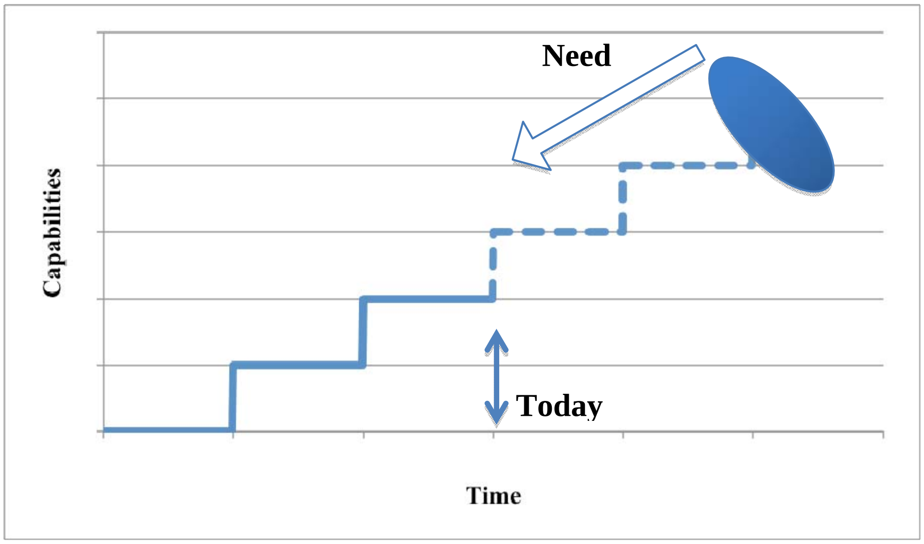

Figure 25. Direction of “Need”

Often, there is an immediate demand for the increased capability, and the question is how this will be achieved by traditional planning. One of the solutions is to compromise. There will still be a gap that will need to be breached and that will take time. If there is no available time, and the demand is great, a technology that has not had time for proper integration or testing may be fielded. It is not the perfect solution. Another solution may be a technology breakthrough. There may be new technology that has matured and will increase capability. For example, a battery using new materials with ten times the storage capacity of current lithium batteries at a tenth of the weight allowed for an immediate jump in the capability of a micro UAV. The UAVs can now be made smaller and fly further than those currently available in the market. Therefore, the previous path of capability increase will follow that of the thicker red line shown in Figure 26. There will be a sudden surge increase in capability which will shorten the time to reach the required capability.

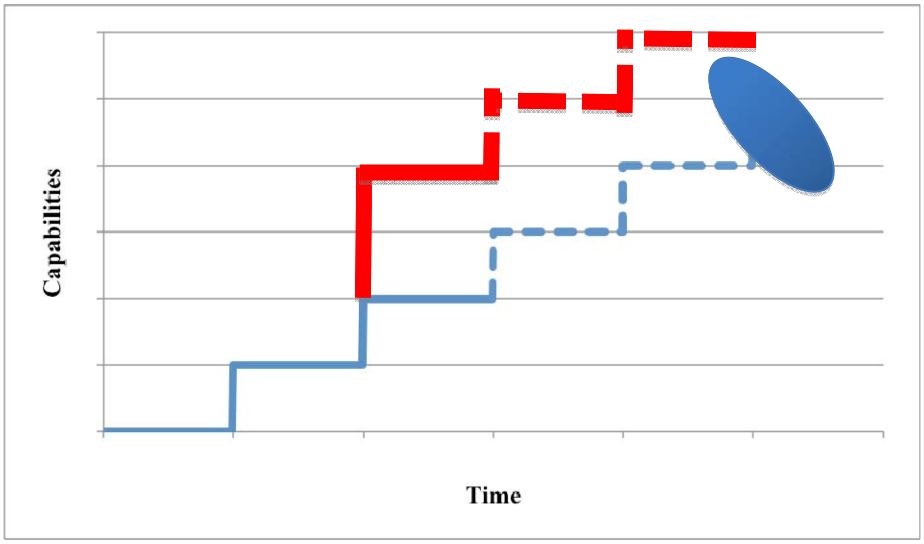

Figure 26. Effect of Technological Breakthrough

It is with the understanding of the duality relationship of “Want” and “Need” that the working processes and benefits of using the slice-of-time scenario become clear. A slice-of-time scenario is set in a future period and the set of conditions comes to fruition in the realm in which the slice-of-time exist is actualized. The shareholders will then be able to better think and feel that environment. The shareholders will then be able to make clearer decisions and have better understanding of the capability gap that exists from the current capability level and the one that exists in the slice-of-time. A path can then be planned to link current capabilities to reach that level of capability that exists in the slice-of-time. The slice-of-time scenario exists in the realm that is depicted as double red lines in Figure 27. It is also with this reverse look from the slice-of-time scenario to today, by which capability gaps can be identified early and resources invested into these identified gap areas, to mitigate or overcome the problems.

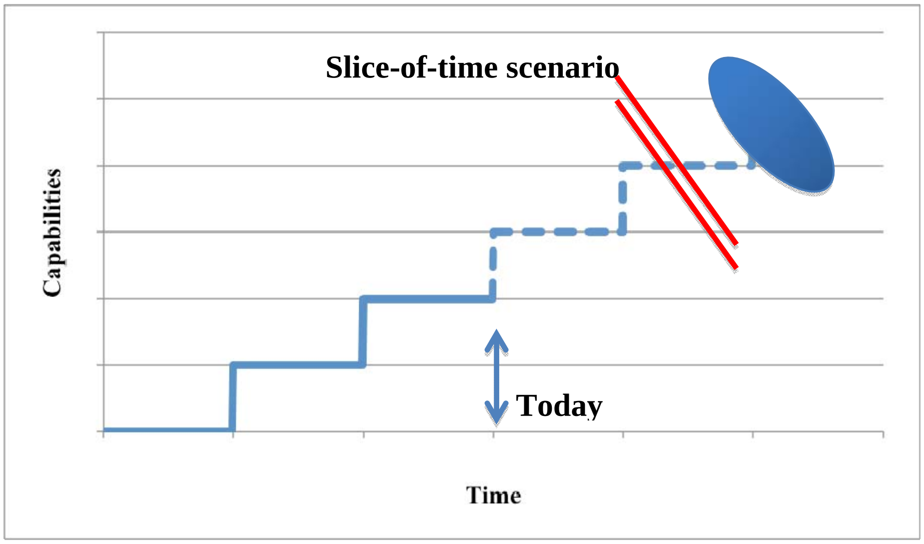

Figure 27. Realm where Slice-of-time Exists

2. A Roadmap to Develop Technology

Figure 28. Roadmap to Develop Technology (After Department of Defense (DoD) 2012)

This thesis proposed the following steps that a project must follow as shown in Figure 28. The steps in further elaborations are as follows:

1. Proposal of a white paper concept. The concept must be endorsed and approved for further effort to be invested.

2. Proof of concept and model. This is will be done in a laboratory environment to systematically test the parts of the white paper concept.

3. Feasibility study and prototype. This next step will conduct a specific feasibility study and to build the prototype to specification in order to conduct more detailed testing and continual proofing of the concept.

4. Demonstration. This is normally done in two stages, one in a controlled environment, the other in the field environment in which the actual equipment is supposed to operate. The demonstration of the prototype's operation in the actual field environment will provide confidence that the product will operate as required in the real environment.

3. A Derived Roadmap for the STARFISH Project

Based on the information of the report papers (and from earlier Section III.B) that the STARFISH project published, a roadmap was devised which explained the STARFISH project to demonstrate its autonomous capability in a field environment shown in Figure 29. Taking into consideration the above four steps, and the real life example of the STARFISH project, a roadmap of integrating unmanned systems to be autonomous and operate in a manned environment is suggested. The roadmap took into account the technological development of STARFISH (from the time of the published papers) and also projected into the near future to see what some of the steps needed to achieve the project's objective will be. It is also assumed that the STARFISH project has a design cycle of three years. This is based on the timeline estimating that it will take about a year to create the prototype design, a year to build the prototype and a year to test and evaluate the design. These cycles are expected to be ongoing until the technology is developed sufficiently to produce an actual working model as shown in Figure 30.

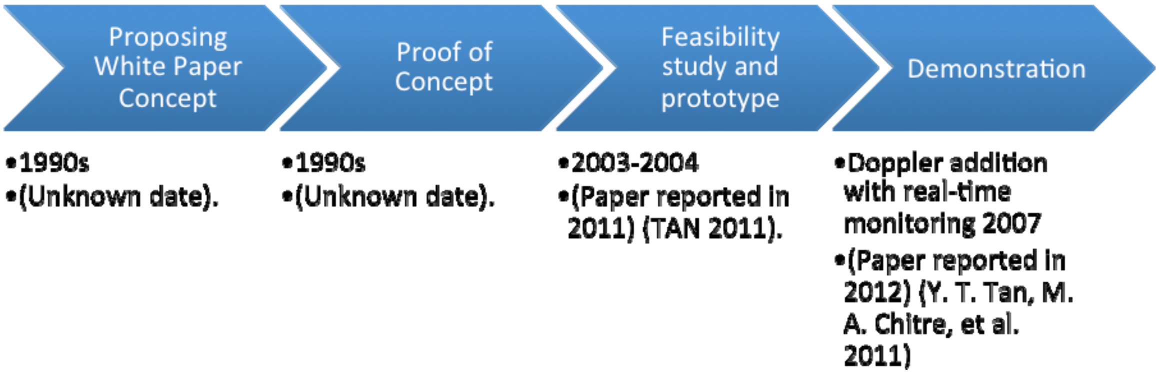

Figure 29. Derived Development Roadmap of STARFISH Project from Paper Published

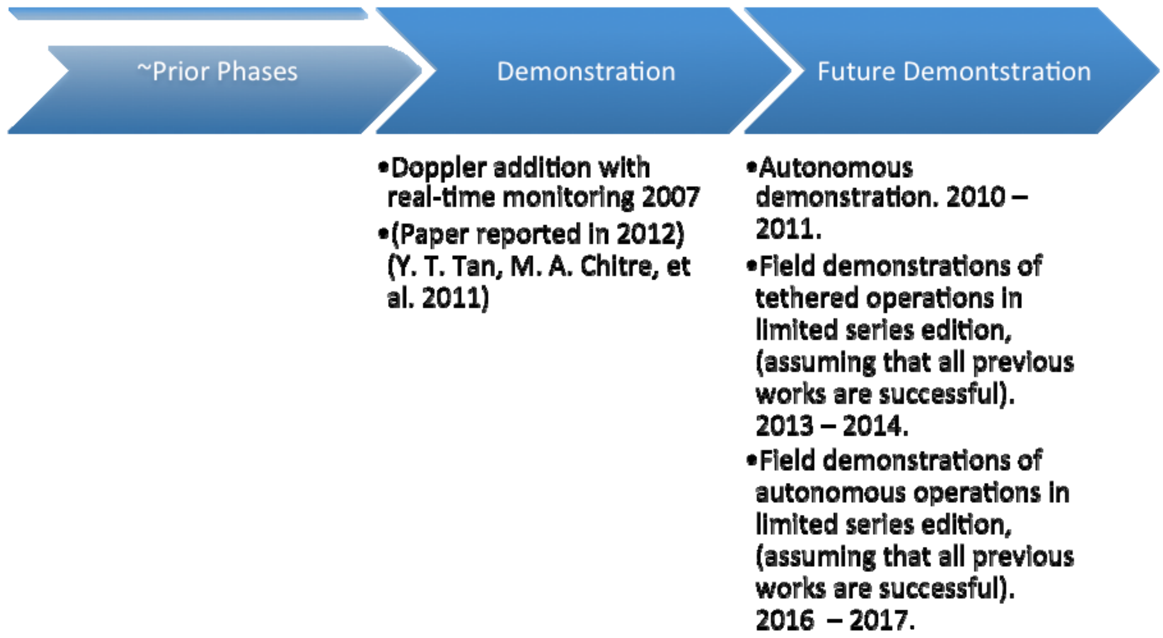

Figure 30. Proposed Roadmap for the STARFISH Project for Future Demonstration

4. Derived Roadmap

Therefore, the derived roadmap for integrating Unmanned Systems is in the following table:

Table 1. Roadmap for Integrating Unmanned Systems

Step	Step Objective	Estimated Year Achieved	Year of Paper Reported
1.	Proposing a white paper concept.	1990s	Unknown date
2.	Proof on concept and model.	1990s	Unknown date
3.	Feasibility Study and Prototype.	2003–2004	2011. (Y. T. Tan, M. A. Chitre, et al. 2011).
4.	Doppler addition with real-time monitoring.	2007	2012
5.	Autonomous demonstration.	2010 – 2011.	
6.	Field demonstrations of tethered operations in limited series edition, (assuming that all	2013 – 2014	

Step	Step Objective	Estimated Year Achieved	Year of Paper Reported
	previous works are successful).		
7.	Field demonstrations of autonomous operations in limited series edition, (assuming that all previous works are successful).	2016 – 2017	

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V. CONCLUSION

A. SLICE-OF-TIME SCENARIO PLANNING

The slice-of-time-scenario planning highlighted the scenario environment of future unmanned systems. The environment was perceived as having the unmanned systems be fully autonomous and prevalent in the future landscape. The unmanned systems would be operating in swarms as command and control (C&C) architecture becomes more robust and should be able to control one-to-many in the future. This thesis suggested the framework of exception C&C to reduce latency as well as provide effective and efficient control in future unmanned systems.

B. ROADMAP TO DEVELOP AUTONOMOUS UNMANNED SYSTEMS

Prior discussion of the United States Department of Defense (DoD) Acquisition Process (described in Section IV.C) gave an understanding of the phases needed to develop technology. Based on published information from the report papers of the STARFISH project, a roadmap was devised and explained (described in Section IV.D.2), that will enable the STARFISH project to demonstrate its autonomous capability in a field environment. The derived roadmap can be used as a guide to implement the full autonomy of unmanned systems and have the unmanned systems integrated in the manned environment.

C. FUTURE WORKS:

This thesis highlighted that to achieve situation awareness in unmanned machines, the challenges to be met are in the areas of comprehension and prediction. To comprehend and predict, situational awareness needs to have an explicitly stated theory and framework for evaluation. This thesis had assumed that theory and framework are present and did not examine these further. One of the potential future works would be to look into the lack of theory and framework for context and evaluation, which is a fault that must be corrected for autonomous operations to become effective.

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